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Mechanical Properties of Masonry Reinforced with Timber Ties

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ABSTRACT: Within a research program carried out at the Laboratory of Reinforced Concrete, NTUA, the typology of historical structural systems in Greece, where horizontal timber ties are used, was studied. On the basis of the typical characteristics of numerous structural systems, an experimental program was designed to study the behaviour of timber reinforced stone masonry subjected to compression or to diagonal compression.

Test results have shown the (expected) limited effect of timber ties on the compressive strength of masonry. It was proven, however, that the wallettes provided with timber reinforcement exhibited substantially smaller crack openings, thus, preventing disintegration of masonry and, consequently, facilitating the application of repair techniques after earthquake damages have occurred. On the other hand, the effect of timber ties on the in-plane shear strength of masonry was substantial; a strength enhancement as high as 100% was recorded.

In the paper, the experimental results are presented and commented.

1 INTRODUCTION

The use of horizontal timber reinforcement within masonry is very common in Greece and in East Mediterranean region since prehistoric times (Tsakanika, 2006). The effect of timber reinforcement to the seismic behaviour of buildings is recognized and qualitatively interpreted. Nevertheless, quantitative information on the subject is not yet available. With the aim to contribute to the study, and, hence, to the preservation of historical structural systems in Greece, a research program was carried out at the Laboratory of Reinforced Concrete, NTUA (Vintzileou et al., 2005). One of the major steps of this program was to study the typology of more than 70 historical structural systems within the country. On the basis of the typology, typical characteristics of the systems were identified (regarding the construction type, the thickness and the mechanical properties of masonry, the arrangement of timber ties, the sectional dimensions of the timber elements, their interconnection, etc.). This allowed for a testing program to be designed, in order to investigate the effect of horizontal timber ties on the behaviour of masonry under compression or diagonal compression. The experimental results served as a basis for the calibration of the analytical work that was carried out within the project. In this paper the results of the experimental part are presented and commented.

2 TESTING PROGRAM

2.1 Description of specimens

The experimental program included eight specimens were constructed, 0.70m long, 0.90m high and 0.50m wide. As mentioned in the Introduction, the dimensions were selected to be representative of a wall pier. The wallettes were made of low quality three-leaf stone masonry. To this purpose, rubble stones (limestone) of a mean compressive strength equal to 50MPa were used, along with low quality (lime-pozzolan) mortar. The compressive strength of the mortar, measured on conventional specimens approximately a month after construction was equal to 0.80MPa.

Among the eight specimens, six were horizontally reinforced by timber elements; the remaining two were unreinforced (reference specimens). Timber elements were of coniferous C30 class. Their cross sectional dimensions were: 60mmx60mm (for the longitudinal elements) and 50mmx50mm (for the transverse elements). Eight (8) mm in diameter stell bars were used in some cases to connect the longitudinal timber elements. A description of the specimens is given in the following sections.

2.1.1 Description of specimens tested in compression

As shown in Fig. 1, three wallettes were tested in compression. Wallette 1 is the reference (unreinforced) specimen, Wallette 2 is reinforced at its mid-height with two longitudinal timber elements connected between them by means of transverse timber elements. The connection between longitudinal and transverse timber elements is made by a nail (length 8 cm, diameter 3.5 mm). This is a poor connection type, typical of the less sophisticated historical systems within the country. In Wallette 3, transverse timber elements were replaced by two 8mm steel bars. This case was examined, since it may constitute a technique of restoring timber ties.

2.1.2 Description of specimens tested in diagonal compression

As shown in Fig. 1, five wallettes were loaded in diagonal compression: Wallette 4 is the reference (unreinforced) specimen. Wallette 5 is reinforced as Wallette 2. Wallette 6 is the equivalent of Wallette 3. Wallette 7 differed from Wallette 5 in that longitudinal timber elements are not continuous. The detail of the in-length connection of timber elements is shown in Fig. 2. This case was investigated because it simulates discontinuous in length timber elements in the normal case where the dimension of the building is larger than the length of the timber elements. The detail selected for investigation is met in the less developed historical structural systems. Wallette 8 contained timber reinforcement in two intermediate levels; transverse connection was provided by timber elements.

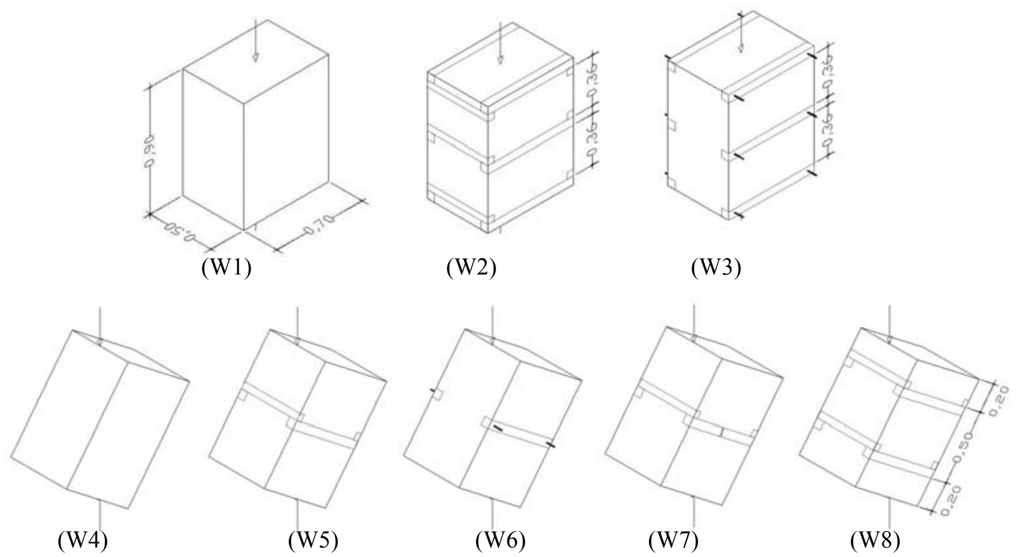


Figure 1 : Geometry of specimens: (W1)-(W3) tested in compression, (W4)-(W8) tested in diagonal compression.

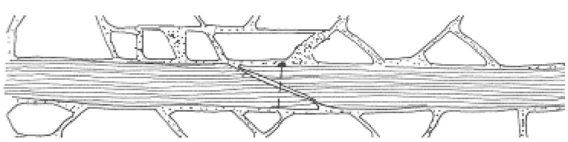
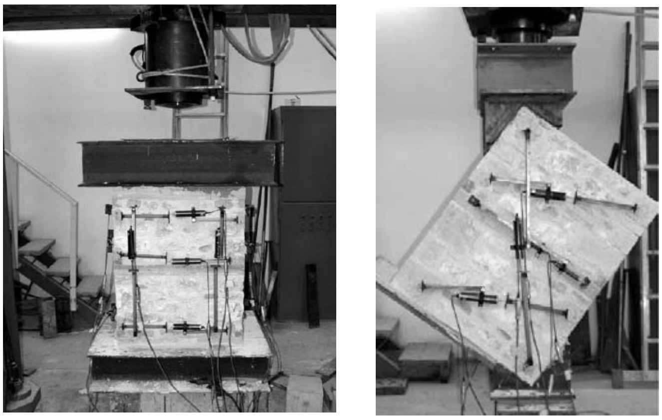


Figure 2 : The in-length connection of timber elements.

3 TESTING SET UP-MEASUREMENTS

Wallettes in compression: The specimens were constructed on a stiff steel base. An identical steel beam was placed on top of each specimen to allow for uniform distribution of the vertical load imposed by a hydraulic jack (Fig. 3a). Vertical, horizontal and transverse deformations and crack openings were measured by means of LVDTs, as shown in Fig. 3a. Axial deformations of longitudinal timber elements were also measured.
Wallettes in diagonal compression: The wallettes were constructed on a steel plate. After hardening of the mortar, they were transferred to their testing position, they were rotated and the steel plate was removed. Each wallette was tested resting on a stiff still corner element (Fig. 3b), whereas an identical steel element was placed at their top to allow for distribution of the applied load, thus preventing local crushing of masonry. Vertical and horizontal deformationsand crack openings were measured by means of pairs of LVDTs fixed on the two faces of wallettes (Fig. 3b). Axial deformations of timber elements were measured as well.



(a) (b)

Figure 3 : Specimens to be subjected in (a) compression or in (b) diagonal compression, in their testing position.

4 EXPERIMENTAL RESULTS

4.1 Wallette 1

The compressive strength of the reference specimen was equal to 0.47MPa. The specimen exhibited the typical failure mode under compression; vertical cracks opened on the two faces (Fig. 4a), passing mainly through mortar joints. The typical behaviour of the three-leaf masonry, consisting in separation between the external stone masonry leaves and the inner filling material was observed. However, due to the low strength of masonry, the opening of cracks on the faces of the wallette was substantially larger (Table 1).

Table 1 : The effect of timber ties on the compressive strength and the deformations of specimens.

Specimen	Load (KN)	Strength (MPa)	strength ratio	Strain at strength	Horizontal deformation (mm)	
					Faces	Transverse
1	164.28	0.469	1.00	0.0062	11.30	5.207
2	201.39	0.575	1.23	0.0201	7.265	2.893
3	182.69	0.522	1.11	0.0124	1.313	11.137

4.2 Wallette 2

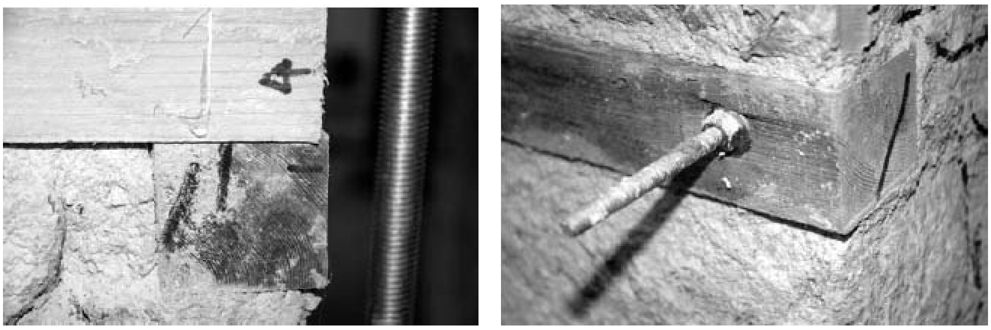
The Wallette 2 failed under a compressive stress equal to 0.58MPa. Its failure mode was similar to that of the reference specimen. Nevertheless, the presence of timber reinforcement resulted to lower values of horizontal deformations (both longitudinal and transverse, see Table 1). The favourable confining action of timber elements is confirmed also by the measurements of axial deformations on longitudinal timber elements. Their axial stress at the moment the wallette reached its compressive strength was equal to 25MPa approximately. The mobilization of timber elements is also confirmed by the cracks observed in their connection (Fig. 4a): the cracks are attributed to the dowel action of the nail connecting the longitudinal and the transverse timber elements. As the timber elements tend to follow the lateral dilatancy of masonry, the nail is subjected to shear that causes splitting cracks to the timber elements at their connection.

4.3 Wallette 3

Wallette 3 reached a compressive stress equal to 0.52MPa. Its failure mode was affected by the connection of the longitudinal timber reinforcement by means of two transverse steel bars. In fact, as shown in Fig. 4c, the horizontal expansion of the wallette under the level of reinforcement was very limited. On the contrary, substantial transverse deformations at mid-height of the wallette were recorded (total opening of cracks equal to 22.3mm). This observation is compatible with the deformation of the longitudinal timber element due to the local compression exerted by the screw nut of the transverse steel bar (Figure 5b). Therefore, one may assume that a more uniform distribution of stresses in the connection between longitudinal and transverse reinforcement would prevent the occurrence of large opening of transverse cracks.

(a) (b) (c)

Figure 4 : Specimens tested in compression. Failure mode.



(a) (b)

Figure 5 : Details of crack pattern, (a) wallette 2, (b) wallette 3.

4.4 Wallette 4

The tensile strength of this wallette subjected to diagonal compression was equal to 0.02MPa. The specimen exhibited the typical failure mode for this type of loading (Fig. 6a): vertical cracks have opened and a strut was formed along the loaded diagonal. Cracks were passing mostly through the weak mortar joints.

Table 2 : The effect of timber ties on tensile strength and deformations of specimens.

Specimen	Load (KN)	strength (MPa)	Strength ratio	Strain at strength	Horizontal deformation (mm) Upper part	Lower part
4	15.78	0.018	1.00	0.0011	2.20	2.00
5	36.91	0.041	2.34	0.0106	18.90	5.20
6	60.80	0.068	3.75	0.0091	13.05	4.15
7	78.69	0.088	5.00	0.0082	10.70	7.90
8	78.39	0.088	5.00	0.0069	7.85	

4.5 Wallette 5

This specimen reached a tensile strength equal to 0.04MPa. Several vertical cracks have opened, distributed over the entire face of the wallette. As shown in Table 2, the sum of the openings of all cracks is several times that of cracks in the reference wallette. However, the disintegration of this wallette being delayed by the presence of timber reinforcement, the specimen reached double the tensile strength of Wallette 4. The mobilization of timber elements is visualized by the slip occurred between longitudinal and transverse timber elements at their connection (Fig. 7a).

4.6 Wallette 6

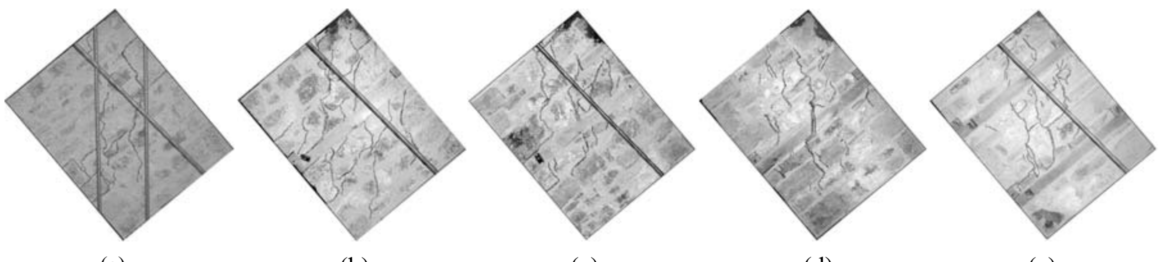
The tensile strength of this specimen was equal to 0.07MPa. In this case (as in the case of Wallette 3), the connection of longitudinal timber elements by means of transverse steel bars proved to be quite efficient. Cracking was limited (compared to that of Wallette 5) and substantially higher tensile strength was reached. It should be noted, however, that some cracks were observed along the masonry-timber interface and some slippage between the two materials was observed (Figure 7b).

4.7 Wallette 7

The tensile strength of Wallete 7 was equal to 0.09MPa. In this specimen, the major crack opened along the loaded diagonal (Fig. 6d); this crack passed through the connection at mid-length of the longitudinal timber reinforcement. Although this connection was achieved only by a nail (Fig. 2) and despite of the substantial opening observed (Fig. 7c), the behaviour of the wallette was satisfactory.

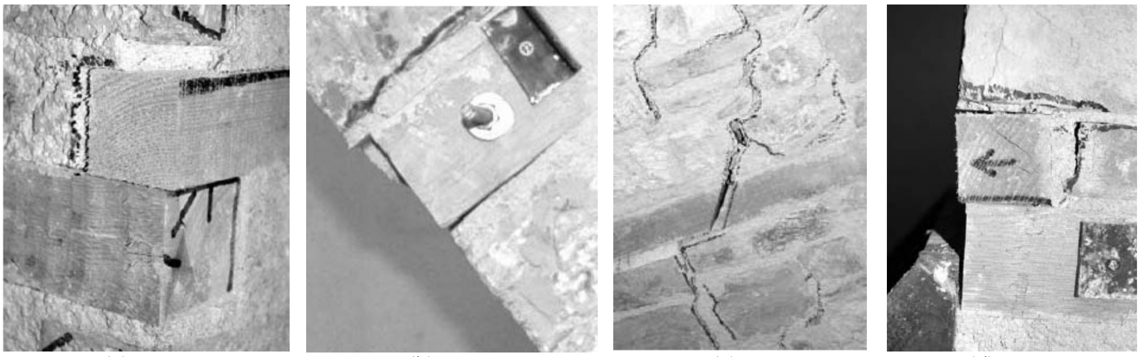
4.8 Wallette 8

This wallette reached a tensile strength equal to 0.09 MPa. It is interesting to observe that the confinement offered by the two timber ties, did not prevent cracks to open along the loaded diagonal. Nevertheless, (a) the cracks are practically limited to the region between the two timber zones, whereas (b) the sum of all crack openings is substantially smaller than for Wallette 5. Due to the fact that lateral dilatancy was limited to the zone between timber ties, slippage along timber-masonry interfaces was observed (as shown in Figure 7d).



(a) (b) (c) (d) (e)

Figure 6 : Specimens tested in diagonal compression. Failure mode.



(a) (b) (c) (d)

Figure 7 : Details of crack pattern, (a) wallette 5, (b) wallette 6, (c) wallette 7, (d) wallette 8.

5 DISCUSSION OF RESULTS

5.1 Wallettes subjected to compression

The compressive strength of masonry (~ 0.52MPa) is quite low, typical for the examined historical structural systems. It should be noted, however, that it is sufficient for the single- or two-storey buildings that typically occur in those systems. This low strength masonry underwent substantial vertical strains (Figure 8a) compatible with the deformability of the weak mortar used for its construction.

It is furthermore observed that the presence of the timber ties does not lead to substantial enhancement of the compressive strength of masonry. This result was to be expected, since the “reinforcement ratio” achieved by the timber ties is rather low.

Nevertheless, the presence of timber ties affects the overall behaviour of masonry in compression. In fact, as shown in Figs. 8b and 9a, thanks to the timber reinforcement, Wallettes 2 and 3 were able to undergo substantially higher vertical strains, than the unreinforced Wallette 1, before they fail, since the lateral confinement provided by the timber reinforcement kept the vertical cracks smaller than in the case of the unreinforced wallette. This is a very important feature for the survival of such low strength masonry.

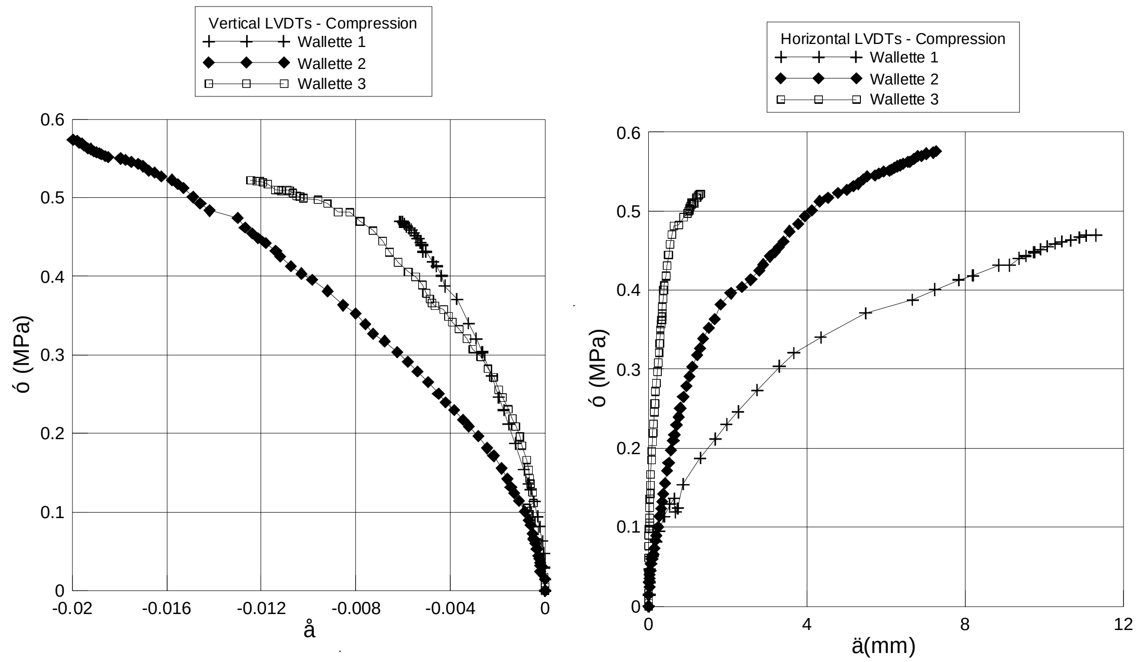
As for the connection of longitudinal timber elements by means of steel bars, it was proven to be an efficient intervention, provided that care will be taken to avoid local crushing of the longitudinal timber element in the connection. In fact, as shown in Fig. 9b, although initially the rate of increase of transverse crack opening is smaller in wallette 3 than for wallettes 1 and 2, when the local crushing of the wood (illustrated in Fig. 5b) has started, the opening of transverse cracks increased substantially.

5.2 Wallettes subjected to diagonal compression

The positive effect of timber reinforcement on the behaviour of wallettes subjected to diagonal compression is illustrated in Fig. 10. Although the failure mode of wallettes 4 to 8 was essentially the same, there have been substantial differences both in the reached strength and in the deformations underwent by the various specimens. More specifically,

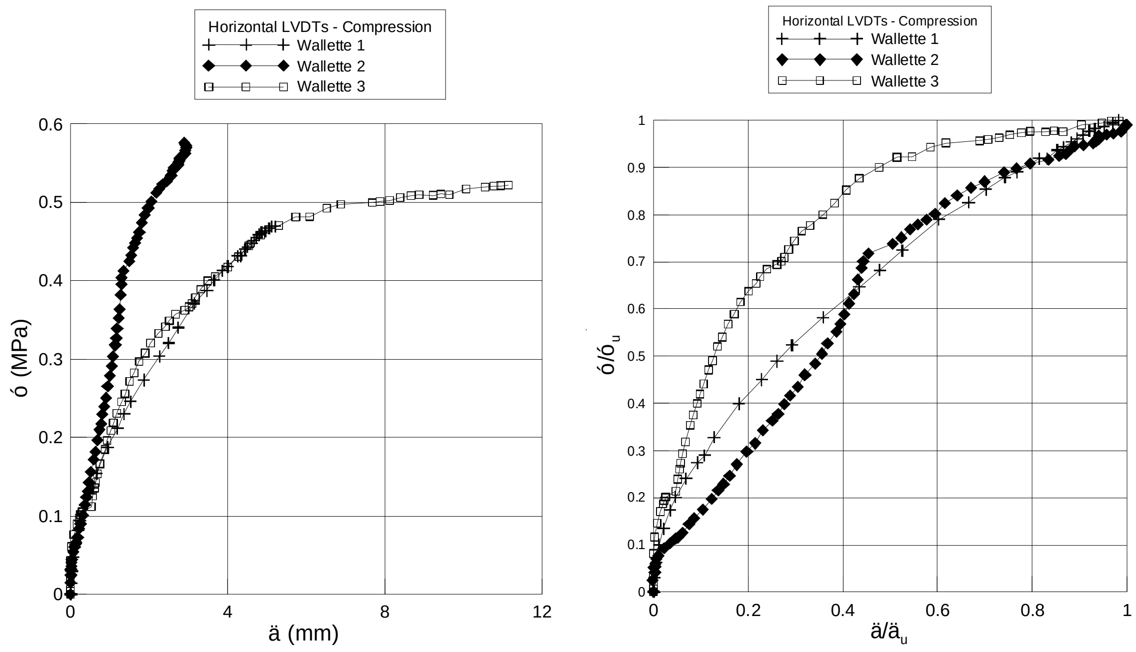
as shown in Table 2, as well as in Fig. 10a, the addition of timber reinforcement led to a substantial increase of the tensile strength of masonry (strength of reinforced wallette normalized to the strength of the reference wallette ranging between 2.34 and 5.00). In addition,

in timber reinforced wallettes, large diagonal crack openings occurred before the attainment of their tensile strength (Fig. 10b). This is a very important feature for the response of structural systems with timber reinforced masonry. In fact, they may undergo substantial earthquake induced deformations without disintegration. Thus, they may survive seismic events and, subsequently, they may be repaired or strengthened and re-used.



(a) (b)

Figure 8 : Wallettes in compression, (a) Stress-strain curves, (b) stress-opening of vertical cracks

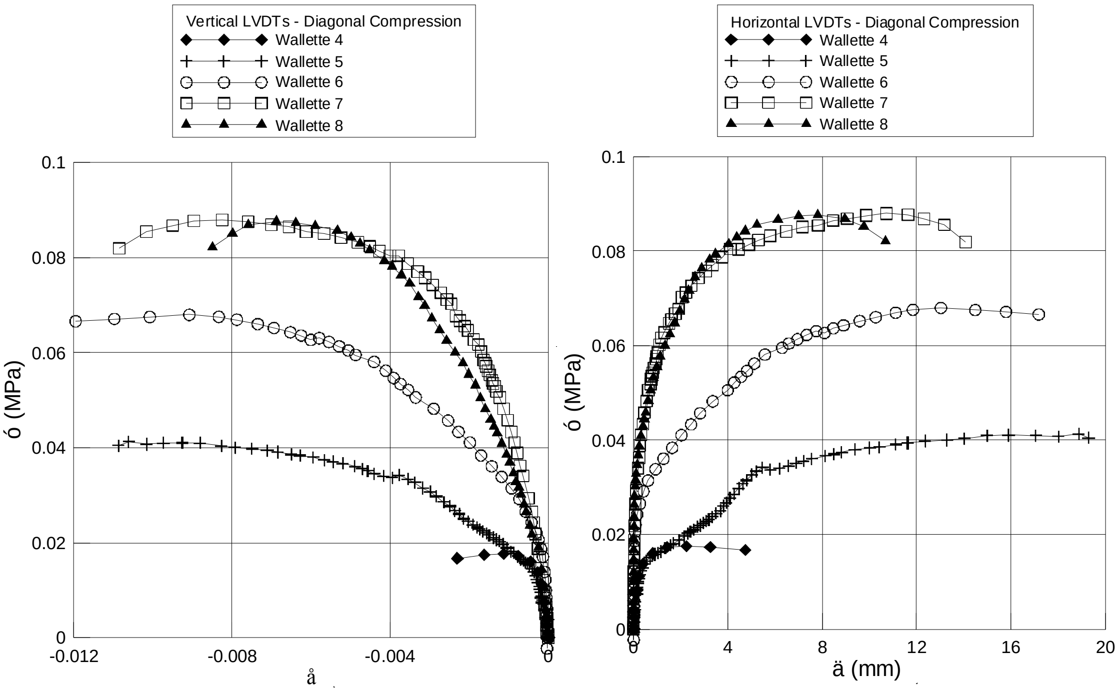


(a) (b)

Figure 9 : Wallettes in compression, (a) vertical stress vs. opening of transverse cracks at mid-height, (b) normalized vertical stress vs. opening of transverse cracks curves at mid-height of the wallettes.

6 CONCLUSIONS

The experimental results presented in this paper confirm the positive effect of timber reinforcement on the behaviour of stone masonry elements; this positive effect is proven by the survival through the centuries of structural systems that were subjected to several seismic events. Taking into account that, during an earthquake, large deformations may be imposed to a



(a) (b)

Figure 10 : Wallettes in diagonal compression, (a) Vertical stress-vertical strain curves, (b) Vertical stress-opening of vertical cracks curves.

structure, one may conclude that the substantial deformations and crack openings underwent by the tested timber reinforced wallettes, before they reach either their compressive or their tensile strength, contribute to their survival after a seismic event. In addition, their strength under diagonal compression (an indicator of their strength when subjected to in-plane shear) was several times that of the unreinforced wallettes. This is another important contribution of timber reinforcement to the seismic behaviour of historical structural systems. It should be noted that analytical investigation of the seismic behaviour of typical buildings (taking into account also the results of this work) is in progress.

ACKNOWLEDGMENTS

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